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Surveys of Soviet-Bloc Scientific and Technical Literature

NUCLEAR WEAPONS EFFECTS

Comprehensive Report

(Report No. 2 in this series)

Aerospace Technology Division
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FOREWORD

This report, the second in a series prepared in response to ATD Work Assignment No. 66, reviews recent Soviet open sources on the effects and simulation of nuclear explosions. The reference material covers the period from 1955 to August 1964. All sources cited are available at the Library of Congress and the Aerospace Technology Division. Full translations of some of the source materials used in this report may be available from other agencies or commercially. Interested readers may obtain translation data for individual sources by indicating source numbers from the bibliography list on the form attached at the end of this report and returning it to the Aerospace Technology Division.

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INTRODUCTION

The preceding issue of this report comprised a bibliography obtained from preliminary processing of Soviet open sources for the period from January 1956 to March 1964. The present issue contains additional materials retrieved from the earlier (January 1955) and more recent (August 1964) sources. Perhaps the most explicit statement of the purpose of this report can be found in a reference book by two outstanding Soviet scientists, Ya. B. Zel'dovich and Yu. P. Rayzer [32]. They said that "the problems of contemporary technology require that science penetrate into the field of 'high parameters' of the state of matter: large concentrations of energy, high temperatures and pressures, and high velocities." In practice, such conditions could be achieved in strong shock waves, explosions, at very high, ultrasonic motion of bodies in air, in gigantic electric discharges, etc.

The present report consists of three sections. The first section deals briefly with the structure and parameters of strong shock waves in solids and in gases. The second section presents a study of the propagation of strong shock waves in compressible media, collisions of such waves at high velocities, and the explosions associated with collisions at such velocities. The last section, entitled Meteorite Analogy, consists of material believed to be of significance in that it reflects Soviet interest in the study of meteorites as a means of simulating the effects of high-power explosions, especially nuclear explosions. The last section also covers one particular case of meteoritic collision, namely the explosion of the Tunguska meteorite/comet of 1908.

Some of the materials presented in the previous report have been quoted again for continuity; these bear the reference numbers 1—31.

I. THE STRUCTURE AND PARAMETERS OF SHOCK WAVES IN GASES AND IN SOLIDS

Thirteen out of thirty-one of the articles presented in the preceding issue of this report dealt with the structure and parameters of strong shock waves and their propagation in gases and in solids. The interest of Soviet scientists in this subject and their intensive treatment of it are important in that the discussion of strong shock wave parameters leads to the explanation of impact and explosion phenomena. The principal authors involved in this line of research are Academicians Ya. B. Zel'dovich and A. S. Kompaneyets, and Yu. P. Rayzer. Both Zel'dovich and Rayzer are well known for their work on shock waves and high-temperature hydrodynamics [32], while Kompaneyets and Zel'dovich have also collaborated on a book on the theory of detonations [33]. The three have also collaborated either with each other (Ze'dovich, Kompaneyets, Rayzer [28, 29]) or other authors (Zel'dovich with Kormer, Sinitsyn, and Kuryapin [9], and Kompaneyets with Lantsburg [31], and also with Andriankin, Kogan and Kraynov [13]). Their findings on the subject of strong shock waves began to appear frequently in print in the latter part of 1957 and have steadily continued since that time.

The early research of Zel'dovich and Rayzer was followed up in two instances. One paper [6] in which the authors investigated the parameters of shock waves with large amplitudes in gases at temperatures up to 500,000°C was followed in 1961 by Losev and Osipov who considered nonequilibrium phenomena that accompany the propagation of shock waves in gases. The result was an extensive survey of the principal methods and results of theoretical and experimental studies of the various relaxation phenomena in shock waves.

There exists a wide class of problems in which radiation transfer occurs in a traveling medium. Broadly speaking, the problem of radiation transfer in a traveling medium reduces to the solution of a system of equations of relativistic radiation hydrodynamics together with the transfer equation. The early work on radiation transfer equations by Zel'dovich [2] and Rayzer [4] was followed by Imshennik and Morozov who in 1964 solved the nonlinear problem of the structure of a shock wavefront with radiation behind it in the case of comparatively low velocities (v), of the traveling medium when $\beta = v/c \ll 1$. In their paper [35], they showed that if all terms approximately equal to β are preserved in the relativistic equation of radiation transfer while the system of equations of radiation hydrodynamics is formulated in a nonrelativistic form, there occurs a qualitative change in the shape of the structure of the shock wavefront.

II. THE PROPAGATION OF STRONG SHOCK WAVES AND THEIR INTERACTION WITH MATERIALS

A. Dynamic Compression of Materials

The general interest in strong shock waves prompted Soviet scientists to study the propagation of such waves in plastic media and the dynamic compression of metals and other materials under very high pressures (up to 4×10^6 atm).

Two articles on the propagation of strong shock waves in plastic media with constant (Kompaneyets [11] (1956)) and variable (Andriankin and Koryavov [12] (1959)) densities were presented in the preliminary report. Unfortunately, no followup material was found in subsequent searches.

In addition, that report contained articles on the interaction of strong shock waves with materials. Among those, two articles published in early 1958 by Al'tshuler and others (Krupnikov, Ledenev, Zhuchkin, and Brazhnik [14]; and Krupnikov, Brazhnik [15]) are of particular interest and have been cited frequently in the subsequent literature on that subject.

In a study of the dynamic compression of metals (Cu, Zn, Ag, Cd, Sb, Au, Pb, and Bi) under pressures ranging from 400,000 to 4,000,000 atmospheres, Al'tshuler and others [15] proposed a reflection method for determining the adiabatic shock curve of a material which requires the measurement of only one parameter, the shock wave velocity. This method, as Al'tshuler suggested in a subsequent article [36], could be simplified further if the shock wave were applied to the specimen through screens made from a material with a known Hugoniot adiabatic of shock compressibility. In this work [36] Al'tshuler and his team investigated phase transformation in water compressed by strong shock waves from 20,000 to 800,000 atm. It is claimed that the methods of investigation were developed under the supervision of one of the authors 10 years prior to the publication of the article and are based on the measurement of kinematic parameters of the shock wave, namely, its propagation velocity (D) and the mass velocity of the material behind the front of the shock wave (U). It was shown graphically that the dynamic adiabatic curve of water is divided into two segments whose ends mark the region of phase transformation. The commencement of phase transformation corresponds to a shock compression of 115,000 atm when D_{H_2O}=5.44 km/sec. At this pressure a reduction in the transparency of water occurs.

Collaborating with Petrunin, Al'tshuler further published at a later date (June 1961) an article [37] on the compressibility of light metals (magnesium, aluminum) and light compounds (water, paraffin, plexiglas) under pressures of 600,000—900,000 atm. In their investigation, they used data from the dynamic adiabates obtained in

Ref. 36. The authors [37] proposed an x-ray method of investigating regular[1] conditions for oblique reflection and collision of shock waves in these substances and for measuring pressures and densities in the region of gradual two-shock compression behind the fronts of reflected shock waves. Particularly high increases in pressure (3.5--4 times) occur in highly compressible substances (paraffin, water, plexiglas), the density of which increased 2.2—2.6 times under these conditions. The angle of reflection in these materials exceeds the angle of incidence of the shock waves. The results obtained for Mg and Al are more similar to the case of collision between acoustic waves. The reflected wave pressures increase approximately 2.5 times for almost identical angles of incidence and reflection. Nonetheless, the densities in the reflected wave are also considerably higher than the densities before collision.

Continuing Al'tshuler's [36] and his own work [9], Zel'dovich, assisted by two of his former collaborators (Kormer, Sinitsyn) and a new one (Yushko) [38], performed a study of the optical properties of water, glass, and plexiglas compressed by shock waves using a reflection method. In the materials studied the reflection of light from the shock front was constant. According to this, compressed water remained transparent across the entire range of pressures studied, from 39,000 to 144,000 atm. In fact, according to their data and in contrast with [36], even under pressures of 300,000 atm. water was still transparent. Glass was not transparent at pressures of approximately 200,000 atm.

In 1960, Zharkov and Kalinin [39] presented a new method of determining the equation of state of metals compressed by shock waves up to pressures of several million atmospheres in general and the equation of state of iron in particular. The formulas developed in their work were not applicable to the somewhat high values of temperature along the shock adiabatic obtained by Al'tshuler and others [14]. However, the zero isotherm obtained by these authors for the high-pressure phase resembled closely the one determined by Al'tshuler [14], being above the latter by approximately 10 atm.

In 1962, Al'tshuler assisted by Bakanova and Trunin [40] carried out additional research on shock compression of metals (Fe, Ni,

1. "Regular" refers to the reflection of shock waves at relatively small angles of incidence with the reflecting boundary. Regular conditions with the 2-shock configuration, consisting of the incident and reflected waves, occur at angles α which are less than some critical angles α_{cr}. Theory of reguler states is elementary and unlike conditions for $\alpha > \alpha_{cr}$ contains only single-valued solutions.

Cu, Zn, Cd, Sn, Pb) at still higher (than in Ref. 37) pressures (up to 9 x 10 atm). The density was found to increase by 1.94 to 2.01 times in Cu, Fe, and Ni; by 2.21—2.36 times in Zn and Cd; and 2.58—2.66 times in Sn and Pb. Al'tshuler also presented extrapolation formulas for zero isotherms and investigated their transition from shock adiabates for all seven metals. The shock compression temperatures at the upper points on the adiabates were 15,000—35,000 degrees for weakly compressible metals (Cu) and 50,000—70,000 degrees for strongly compressible ones (Zn, Sn, Cd, Pb). Al'tshuler also claims that Zharkov and Kalinin [39], who used an equation for zero isotherms in a form similar to Al'tshuler's, have employed the experimental data for pressures up to 10^6 atmospheres to determine the parameters of the equation of state. In this equation, the Gruneisen coefficient for electrons had an unusually high value and extrapolation of their adiabate in the region where the Hugoniot pressure is greater than 5×10^6 atmospheres contradicts the experimental results obtained by Al'tshuler [40].

B. Collisions of Shock Waves and Metals at High Velocities

We indicated in the preliminary report that Al'tshuler, in collaboration with five others [16], had investigated the subject of collisions of high-velocity shock waves. In this article he proposed a method of producing and recording irregular[2] conditions of oblique collisions of shock waves and presented the results of his measurements of the parameters of three-shock configurations due to collisions of shock waves with amplitudes between $3—4 \times 10^5$ and $1—1.8 \times 10^6$ atmospheres for four metals (Fe, Al, Cu, Pb).

Broadly speaking, there exists but one step between collisions of shock waves [16] and collisions of metallic bodies at high velocities. The latter was experimentally investigated by Zlatin [41] for the case in which the thermodynamic parameters of bodies (lead, copper, aluminum, iron) are not yet complicated by their explosion. The data for the shock adiabate and the dependence of the Gruneisen coefficient on the specific volume were supplied from the works of Al'tshuler [14, 15]. The experiments were performed under conditions in which the bodies interact in both the steady and transient states. In these states the metals were considered as compressible liquids with corresponding densities. The threshold velocities at which colliding bodies explode were found to be 2.2—2.4 times higher in the steady state than in the transient one. Moreover, threshold conditions in the first case can be attained when the densities of colliding metals increase by 60—70% and by 50—60% in the second case. The threshold values of impact velocities in the transient state are 3—4 km/sec only for metals with relatively low binding

2. "Irregular" refers to the reflection of air waves. [See footnote on p. 4.]

energies. In this category bismuth, cadmium, and arsenic can be considered in addition to lead and zinc. Metals with high values of binding energy, such as iron, copper, and aluminum have even higher threshold velocities at impact (6.55—8.35 km/sec) when colliding in a transient state.

More recently (July 1963), Andriankin [42] theoretically investigated the problem of collision of two plates at high velocities when solids are vaporized as a result of impact and the resultant gas is scattered into vacuum. Andriankin showed that almost all the energy of the gas is transmitted in the direction of impact and a considerable decrease in energy flow occurs only in the case of impact against a thick target. For example, when the mass of the obstacle is 25 times greater than the mass of the impacting body, at least 50% of the energy is still transmitted. An increase in the density of the impacting body amplifies the directed action. When two plates with identical density and thickness (for which the intensity of shock waves is constant) collide, the solution of the problem is exact and adiabatic (isentropic) and it holds for a series of discrete values of γ (coefficient of the shock adiabatic). If, however, the densities of the target and the impacting body are different, an exact solution was found to exist ($\gamma=3$ only). In the case in which the thickness of the target and the body are arbitrary, the problem can be solved by means of an approximation method based on the distribution of density as a polynomial with arbitrary coefficients.

A team of authors headed by Belyakov and including Zlatin recently published (March 1964) a paper [43] on the impact of deformable bodies and its simulation. They have shown by means of direct measurements that there exists a correspondence between the instantaneous values of the deforming and force parameters in the simulated and simulating processes. Using pulsed x-ray techniques, they photographed the penetration of a cylindrical impacting body (heat-treated soft steel and annealed copper with specific gravities of 7.85 and 8.9 g/cm^3, respectively, and dynamic hardnesses of 67 and 65 kg/mm^2, respectively) into cylindrical "semispaces" (heat-treated dural and annealed aluminum with specific gravities of 2.8 and 2.7 g/cm^3, respectively, and hardnesses 67 and 26 kg/mm^2, respectively) at velocities of 1380 m/sec (for steel) and 870 m/sec (for copper). In both cases, the final penetration was identical and equalled 35.5 + 0.5 mm and the times taken to penetrate dural by steel and aluminum by copper were 68 and 100 msec, respectively.

C. Explosions of Solid Bodies at High Velocities

When investigating phenomena which occur during a strong explosion it is of interest, according to Sedov [44] (the author of a well-known classic on similarity methods and dimensional analysis in mechanics [45]), to establish the relationship between the velocity of a shock wave and its distribution with respect to the point of explosion. Since the pressure discontinuity and the ve-

locity and density of gas particles are determined by the velocity of the shock wave and the initial composition of the gas, the magnitude of these parameters governs the mechanical effect of the explosion reaction. The problem is solved by assuming a point explosion in which: 1) the energy liberated is infinite; 2) the (ideal) gas is in a steady state under no initial pressure (atmospheric pressure $\ll$ pressure behind the shock wave); 3) the flow behind the shock wave front is adiabatic; and 4) the explosion occurs in a medium with constant density. Under such assumptions, the problem of a strong point explosion is solved for cases of spherical, cylindrical, and plane waves. In the center of the explosion, the velocity and density are zero while pressure tends to zero with time; the latter means that the gas flows in the reverse direction (toward the center) with attenuation of the shock wave.

The possibility of occurrence of an explosion when solid bodies collide at high velocities was first investigated by Stanyukovich and Fedynskiy [46] in 1947. In this article they made a study of complex phenomena (formation of a crater accompanied by ejection of dust and gases, radiative and thermal effects, generation of a strong shock wave, meteoritic ablation) which accompany meteoric collisions and which, until then, were studied only qualitatively. While investigating the lunar crater theory [46], Stanyukovich assumed that a shock wave generated by impact on the lunar surface is propagated in the same manner as when generated during a strong explosion (with a given energy) in an infinite medium in which the pressure and specific internal energy are both inversely proportional to the mass of a body. However, like Zlatin [41], Stanyukovich and Fedynskiy have only considered the parameters of a process under conditions in which collisions between bodies had not yet become complicated by explosions.

Further theoretical research concerning point explosions was carried out in 1955 by Sedov's associate Karlikov [47]. Whereas Stanyukovich and Fedynskiy [46] assumed that the explosion occurred in a medium with constant density, Karlikov investigated media with variable density. In his work Karlikov presented a linearized solution of a problem of a strong point explosion in a gas, set up as one involving a system of equations of gas dynamics for a centrally symmetric, adiabatic, nonsteady flow.

The subject of a strong point explosion in a gas continued to attract contributions. In 1956, Korobeynikov published a paper [48] in which he theoretically investigated the problem in which the temperature gradient is zero. His work is analogous to Sedov's [44] except for the fact that the motion of gas behind the front of a shock wave is not adiabatic, but instead, intensive heat transfer takes place. As a result of this, the temperature gradient in the turbulent flow region is assumed to be zero. All other assumptions made by Sedov are also applied to this problem. As a result of computations, Korobeynikov found that the gas remains at rest in the

region between the center of the explosion and approximately 1/2 radius of the shock wave. As the distance from the center of explosion increases further, the velocity of the gas increases linearly.

A study of powerful explosions in a real gas was made by Anisimov [49] in 1960. His work represents an advance over the ideal gas problem studied by Sedov [44]. As an example of a medium representing an essential departure from the properties of an ideal gas, Anisimov considered water with constant heat capacity and, like Korobeynikov's work [48], centrally symmetric adiabatic motion. Anisimov also presented a graphical representation of the distribution of velocity, pressure, and density behind the shock wave in an underwater explosion.

The problem of a point explosion in a highly rarefied atmosphere was investigated theoretically by Academician Kompaneyets [50]. He proposed a partly qualitative approach which is based on an essential property of a point centrally-symmetric solution. In this type of solution, the energy is distributed almost uniformly through the whole volume of the explosion wave, and only close to the front does the energy density exceed by two or three times the mean value through the volume. It is in this region that all the mass is concentrated. It is natural to assume, Kompaneyets claims, that this phenomenon takes place in an explosion wave in an inhomogeneous atmosphere. The coefficient giving the ratio of the energy density at the front to the mean energy density through the volume is assumed to be constant over the surface. This assumption forms the basis of the method proposed and permits analytic solution. The solution loses its value, however, when the shock wave escapes upward from the point of explosion by an appreciable distance. No matter how great the energy of the explosion a strong wave, according to Kompaneyets' results, cannot penetrate downward further than approximately 11 km. Below this depth the shock wave will be rapidly weakened.

Whereas Kompaneyets proposed an approximate solution [50], a subsequent study by Andriankin, Kogan, Kraynov, and including Kompaneyets [13] provides a more exact solution of the problem of a strong explosion in an inhomogeneous atmosphere. They showed that the strength of a shock wave diminishes unequally in different directions with the largest decrease taking place in the direction of increasing density, that is, toward the earth. The depth of penetration of a shock wave, independent of the strength of the explosion, was established at less than 16.5 km. Furthermore, they have developed formulas for calculating the velocity and pressure in an expanding shock wave as a function of time for different energies and altitudes of explosions.

Closely associated with, but stricter than the two former studies [13,50], was a research project carried out in 1963 by Rayzer [51] who investigated the motion produced in an inhomogeneous atmosphere (in the direction of increasing density) by a plane shock of short duration generated by an explosion. He found, by using real

computed values of the parameters, that in the process of retardation of a shock wave down to a velocity of the order of 1 km/sec, which exceeds the velocity of sound in cold air, the shock wave is propagated downward a distance of the order of 2—3 magnitudes in addition to a distance of approximately 2 magnitudes suggested later in [13, 50].

In August 1964, Rayzer published a paper [52] in which he solved this problem for a plane shock wave in an inhomogeneous atmosphere, but, in this case, in the direction of decreasing density which varies exponentially in space. In the same paper, he also considered the self-similar flow of gas into vacuum which takes place when a shock wave disappears to infinity. The self-similar flow equations were solved numerically for two values of the adiabatic exponent $\gamma = 5/3$ and $\gamma = 1.2$. The latter value approximately corresponds to the developed and near-equilibrium ionization of a gas at high temperatures, while $\gamma = 5/3$ corresponds to an arrested degree of ionization at extremely low densities. The obtained solutions can be used for an approximate description of the flow field in the upper regions above the level where strong explosions occur in a inhomogeneous atmosphere. Rayzer concludes, in principle, that the air accelerated upward by a shock wave to high velocities should be able to escape the earth's gravitational pull and to 'spill' into the space. However, due to the strong ionization, the flight upward is arrested by the braking action of the earth magnetic field.

According to Chernyy [53], the hypersonic motion of a thin, blunt body in a gas and a strong explosion of a cylindrical charge can be considered analogous. In his paper published in 1963, Chernyy had shown the variation in the coefficient of resistance of a thin, blunt wedge and of a thin, blunt cone graphically as a function of their length. These two parameters show an inversely proportional relationship. In certain characteristic cases of flow, the resistance of a blunt cone can be almost the same as the resistance of a sharp cone, whereas, the resistance of a blunt wedge exceeds the resistance of a sharp one in such cases. Chernyy further emphasizes the fact that the theory of flow past thin, blunt bodies refers, strictly speaking, only to such bodies whose entire surface can be divided into a small frontal blunt part where the angles between this surface and the direction of flow are of the order of $\pi/2$, and the remaining part where these angles are small. For such bodies, the flow region can be divided into an "internal" entropy layer in which the density of gas is low, and an external turbulent flow in which the law of plane cross sections can be satisfied. The above problem can be considered asymptotically as the one concerning plane flow which occurs during explosion in a cylinder with a subsequent displacement of the piston.

III. METEORITE ANALOGY

A. Meteorite Collisions

A study of processes which accompany the motion of meteors through the earth's atmosphere represents a scientific interest which can be viewed from various standpoints. One such standpoint is offered by certain Soviet authors who consider the meteorite problem as a working simulation of the explosion problem. In this section of the present report only these articles which deal explicitly with meteorite explosions will be considered.

It was pointed out (see p. 7) that Stanyukovich and Fedynskiy [46] were the first to suggest the possibility of explosion due to the collision of solid bodies at high velocities. In a paper [54] delivered at the First Conference on Meteorites called by the Committee on Meteorites of the Academy of Sciences, USSR and held in Moscow on 16-19 March 1949, Stanyukovich added that both the nature of fragmentation of meteorites at velocities of 10—500 m/sec and their subsequent vaporization at velocities of 4—5 km/sec can be regarded as explosive. The total explosion of a meteorite occurs during vaporization while its fragmentation appears as an explosion of lower intensity.

At first Stanyukovich and Fedynskiy [46] and Zlatin [41] (see Section II) considered only the parameters of a process in which the collision between bodies (meteors) had not yet been complicated by their explosion. In 1956, Stanyukovich alone published a paper [24] in which he analyzed the interaction of two strong shock waves (pressures greater than 10 kg/cm^2) of equal intensities generated as a result of meteorite explosion in terms of an equivalent problem, that is, reflection of a shock wave from rigid wall.

In 1959, Stanyukovich published another paper [55] in which he theoretically investigated the impact of solids (meteors) at high velocities accompanied by explosion. At high impact velocities ($\mu_0 > \sqrt{\varepsilon}$, where ε is the strength of the medium), the mass M expelled from the medium by the explosion exceeds considerably the incident mass and, therefore, the momentum J of the expelled mass also exceeds considerably the initial momentum $J_0 = Mu_0 \cos\theta$, where θ is the angle (from normal) at which the impact takes place. Experiments and computations have shown that the exploded and expelled mass $M \approx E_0/\varepsilon$. Since the momentum of the expelled mass is $J \approx \sqrt{ME_0}$, where E_0 is the initial energy of the expelled mass, then obviously $J = AE_0/\sqrt{\varepsilon}$, where A is some experimental coefficient related to strength properties of the medium. At cosmic impact velocities, on the order of 30 or 40 km/sec, $J > J_0$ by one order of magnitude.

When high-velocity meteorites impact a planetary surface without atmosphere (for example, the Moon), a cloud of vaporized matter is

formed which in turn expands into vacuum. This phenomenon, Rayzer says [56], is to some extent similar to explosions in, for example, electrical wires in vacuum, pulsed x-ray tubes, etc. The kinetics of condensation of such clouds and metallic vapors in vacuum were considered by Rayzer in 1959, using a simple gas model under laboratory conditions. Rayzer suggested that when large meteorites strike a planetary surface without an atmosphere, a part of the surface and the body of the meteorite may evaporate and subsequently condense and that this process may be one source of cosmic dust.

The impact of a meteorite against a planetary surface without an atmosphere was further considered in 1964 by Rayzer [57] in a two-dimensional approximation as a point explosion on the interface between empty space and an ideal gas. The latter was used as a model of the impact-heated vaporized "soil". Assuming a meteorite velocity of the order of 10 km/sec, the relationship between the shock wave pressure and the affected mass is $p \sim M^{-n}$, where $1 < n < 2$. The determination of the numerical value of n is based on a simple centered wave equation. His results show that the derived law of attenuation of the shock wave is very similar to the one for the case of an explosion in an unlimited medium. This adds further support to the assumptions introduced by Stanyukovich [46].

In 1961, Stanyukovich and Shalimov [58] and, independently, Pokrovskiy [59] suggested possible mechanisms of meteoric explosion. Pokrovskiy explained how the tail of a meteor affects the motion of its head portion. He had also pointed out that this tail, an incandescent trail of ablated meteoric mass, considerably affects the last stage of travel of a meteor—the explosion of meteoric mass, particularly when the explosion takes place in the air. In such a case, the expanding gases generated by the explosion are outwardly enveloped by the front of the air-shock wave whose shape is, normally, a sphere. However, the presence of a high-temperature meteor trail means that the shock wave travels much faster along the trail and, in doing so, disturbs the spherical form of the front of the shock wave. Thus, the meteor trail acts as a waveguide along which the shock wave generated by the explosion is propagated at an elevated velocity. This further leads to a transfer of additional energy from the explosion into the tail region and amplifies the general effect of the explosion in the tail hemisphere.

In the same paper Pokrovskiy proposed a laboratory setup for modeling an equivalent 100-megaton meteoric explosion. In his experiment he used a scale whereby a 1-gram charge produces an explosion equivalent to 100 megatons and a distance of 2.16 cm corresponds to 1 km. He assumed here that the earth's surface is horizontal and flat, and represented it by means of steel with a net of microcrusher gages. The latter were separated by holes 5 mm in diameter in a steel plate covered by a thin aluminum foil. After an explosion the foil is slightly but permanently deformed and the degree of deformation can be regarded, under fixed experimental conditions, as proportional to the excess pressure at the air shock wave. This enables one to determine the distribution of pressure in a wave which travels

along the flat surface of the earth during an explosion at any altitude above the surface. In order to reproduce the incandescent meteor tail, the entire model was arranged in such a way as to make theaxis of the meteor tail vertical. The hot trail itself was simulated by a flame. The experimental values (the ratio R_3/R_1, where R_1 is the front and side radius of the shock wave which produces a certain effect, and R_3 is the radius at which a corresponding effect would be produced by the shock wave in the absence of the meteor tail), obtained by means of this model are somewhat lower than the theoretical values. This is due to the fact that the value of the solid angle subtended by the conical flame was considerably smaller in the experiment than in the computation. A correction for this angle would result in satisfactory agreement of the experimental and theoretical results.

A comparison of the geometry of craters formed by impacting meteorites and surface nuclear explosions was made in 1964 by Ryabinin, Rodionov, and Dremin [60]. They considered the problem of the size of a crater as a function of the mass and velocity of the meteorite and extended this approach to the case of craters produced by nuclear explosions. The nuclear explosions indicated that in the case of large scales the linear dimensions of craters vary unequally with an increase in the energy of the explosion. This makes modeling that utilizes the methods of geometric similitude difficult. This scale effect is associated with the action of the gravitational field and requires special investigation. It occurs, nevertheless, in both meteorite impacts and explosions. The three authors claim that their formulas hold for relatively small craters approximately 200 m in diameter.

B. The Tunguska Meteorite/Comet

The impact of the Tunguska meteorite, which fell on June 30, 1908, left an appreciable imprint on the Soviet meteorite physics. Numerous Soviet authors agree that the Tunguska meteorite exploded in the air at about 6—9 km above the ground and compare the explosion to a nuclear blast [61, 62, 63, 64]. The interaction of the shock wave generated by the explosion with the geomagnetic field caused variations in the latter. The magnitude, form, and duration of such variations are similar in nature to the geomagnetic effects caused by high-altitude nuclear explosions [24] or sudden, but brief magnetic storms [65].

Thus, the geomagnetic effects observed at the Irkutsk Magnetic Observatory 2.3 min following the explosion of the Tunguska meteorite indicate [25] that the largest variations occurred in the H-component. The initial field increased by 20×10^{-5} oe during the first 20 min, remained constant (within 10^{-5} oe) during the next 12 min, then diminished by 67×10^{-5} oe during the next 54 min. The Z-component changed by 28×10^{-5} oe. Ivanov, who made this [25] and other [66] studies, offers an explanation as to why these variations are attributed to the explosion of the Tunguska meteorite. In a manner simi-

lar to the effect of high-altitude nuclear explosions, the observed effect was attributed to propagation of the shock wave generated by the explosion of the meteorite through a region in the E-layer of the ionosphere. The life of such region, with locally increased conductivity, and its effect on the geomagnetic field are considered important. According to Ivanov [25], Florenskiy [61], and Fesenkov [67], the sharp and sudden disturbance in the geomagnetic field and, according to Fesenkov [67], the reverse motion of the meteorite constitute independent proofs that the Tunguska meteorite exhibits the characteristics of a comet. Fesenkov claims further that the impact of this meteorite is today the only known and reliable collision of a comet with the earth.

The variation of the geomagnetic field was calculated by Obashev [26] and found to be, in general, in agreement with the amplitude of the disturbance recorded at Irkutsk. Using a mechanism described in [20] he provided an explanation for the delayed occurrence of the geomagnetic effects observed 2.3 min after the explosion of the Tunguska meteorite. It is shown that the delay time was equal to the period (τ) during which the plasma formed in the explosion ceased to expand in the direction transverse to the geomagnetic field. During τ, the plasma remains quasi-neutral and, since charges are not separated, no geomagnetic effects occur. Obashev failed, however, to allow for the fact that the meteorite exploded in the lower atmosphere where the gas pressure is almost 10^{-6} times higher than the magnetic pressure.

Plekhanov and others [65, 68] collaborated with Ivanov on processing the Irkutsk magnetic records and obtained compatible magnitudes of variations in the geomagnetic field. Comparison of magnetic effects due to nuclear explosions and a meteorite explosion indicate [68] the following common features: 1) the disturbances have sudden origins; 2) the general variation in the H-component of the geomagnetic field is identical in both cases; 3) the disturbances in the Z-component observed at Irkutsk, Fenning, and Honolulu Observatories (the latter two took part in observations during the U. S. nuclear tests, 60 and 30 km above Johnston Island on 1-12 August 1958); 4) with respect to the general behavior of the H- and Z-components, the differences between both effects lie within the limits of differences observed at individual stations in the case of nuclear explosions; 5) the total duration of a disturbance is approximately equal to 1—1.5 hr for nuclear explosions and 4—5 hr for the meteorite explosion; 6) in both cases the disturbances were local in character since no disturbances from nuclear explosions and meteorite explosions were recorded at Guam and Sverdlovsk Observatory, 4000 and 2500 km from the epicenter, respectively. The most significant difference lies in the fact that in the case of nuclear explosions, a sudden pulse is observed immediately after the explosion, whereas in the meteorite explosion the disturbance in the geomagnetic field took place some 2.8 min after the explosion.

While studying the magnetic effect due to nuclear explosions,

H. J. Maeda (Geoph. Rev., v. 64, no. 7, 1959) concluded that explosions carried out on the surface appear to have no effect whatsoever on the geomagnetic field. This seems to indicate, Plekhanov claims [68], that in the case of low-altitude bursts the energy of the shock wave is dissipated before it reaches the upper layers of the atmosphere. Since the explosion energy of the Tunguska meteorite ($\sim 10^{23}$ erg [61, 62, 63, 4]) was hardly higher than the energy liberated in nuclear blasts in the Johnston Island tests, it would seem that the shock wave was incapable of causing the observed effect. It is, however, possible that the mechanisms of the magnetic effects due to the meteorite explosion and those due to nuclear bombs are totally different. It is further possible that the meteorite exploded sufficiently high over the earth's surface and the energy of the shock wave was not dissipated until the wave reached the E-layer of the ionosphere.

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